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Enhancing the Error Performance of Optical SSK under Correlated Channel Condition

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Abstract—This paper presents ways of enhancing the performance of spatial shift keying (SSK) in optical wireless communication systems with correlated channel gains. One method involves varying the pulse width and the other involve varying the pulse amplitude to provide additional differentiation to the signal transmitted by each optical source. Closed form expressions are derived for the error performance and are validated with computer based simulations. When compared with the conventional SSK for the correlated channel gains under consideration, these enhancements methods could result in up to 20 dB reduction in signal-to-noise ratio at a symbol error ratio of 10^{-6} for a four-transmitter, one-receiver configuration.

I. INTRODUCTION

Various techniques exist in wireless communications to exploit the spatial position occupied by an antenna and/or receiver. Common ones include spatial diversity to provide resilience against debilitating channel conditions, spatial multiplexing and spatial modulation (SM) for increased throughput. These techniques have been extensively studied and reported in the listed literature and the references thereof [1]–[5].

When processing power is limited, the SM represents a low complexity multiple-transmitter approach to increase data rate [6], [7]. Using only the spatial position occupied by the transmitters to convey information is termed spatial shift keying (SSK) [8], [9] but adding another layer of signal constellation on to the SSK results in SM [10]. In the conventional SSK, only one transmitter is active during a given symbol duration. Also the number of transmitters in the conventional SSK is usually a power of two. Hence with a total of N_t transmitters, the SSK achieves $\log_2 N_t$ bits per symbol transmission from every transmitter.

Both SM and SSK rely primarily on the fact that the wireless communication channel gains vary with the relative spatial positions of the transmitters [5], [8], [11], [12]. In radio wireless communications, this is certainly the case in the presence of multiple wave scattering, reflection and node mobility. In optical wireless communications where there is no fast fading, the channel is rather static and the channel gains are more likely to be correlated than in radio wireless systems;

especially when the transmitters are closely located. This motivates the work presented in this paper. Here, two approaches that can be implemented to enhance the performance of SSK in optical wireless communications systems with correlated channel gains are presented. The techniques involves adapting the properties of the pulse from each optical source to the channel conditions. In one of the enhancement approaches, the pulse width is varied while the amplitude is varied in the other to provide additional differentiation to the signal transmitted from each optical source. Although the emphasis in the work will be on SSK in indoor optical wireless communications, the methods discussed could also be applicable to SM.

The rest of the paper is organised as follows: the conventional SSK is briefly introduced in section II, the enhancement methods to make SSK adaptive are introduced in section III, results and discussions are presented in section IV while section V gives the concluding remarks.

II. OPTICAL SSK IN CORRELATED CHANNEL CONDITIONS

The optical SSK technique exploits the spatial dimension to increase spectral efficiency. It represents a low complexity multiple-input technique in which the spatial position of each optical source translates to a signal constellation point. The SSK with its N_t bits per symbols transmission compares with a pulse amplitude modulated (PAM) system with N_t distinct pulse amplitude levels. The difference here is that in the SSK transmitter, the transmitted pulses from all the LEDs have the same amplitude. Symbol differentiation and detection at the receiver is aided by the location dependent channel gains. Also, the SSK is simpler to implement compared to an identical PAM system [8]. With PAM, there is the risk of operating the LED beyond its dynamic range (into the nonlinear region) particularly as the number of levels increases. On the hand, SSK has only one signal level per LED, thus this risk can be easily eliminated with an increased number of LEDs. Also a single LED lamp often contain multiple light sources, this is what SSK exploits to increase data rate.

Consequently, the error performance of the SSK is strongly related to the difference between channel gains. For any given

pair of channel gains h_i and h_j , the error performance of an SSK system deteriorates considerably whenever these gains are correlated; that is $h_i \approx h_j$. This could be due to the close proximity of the optical sources. This is a possible scenario in visible light communications (VLC) when closely located multiple illumination LEDs are also used for wireless communication.

According to the work presented in [12], when there is strong correlation between any two given channel gains, it is almost impossible to establish a reliable optical wireless communication link based on optical SSK. This then led to the suggestions that SSK is best suited for a fixed configuration where the nodes are immobile and the channel gains are distinctive [12].

III. ENHANCED OPTICAL SSK IN CORRELATED CHANNEL

To address the correlated channel problem, we will be considering the following two approaches to enhance the error performance of SSK in this section.

A. Optical SSK with Variable Pulse Width (eSSKv)

An illustration of this scheme for the case of $N_t = 4$ is shown in Fig. 1. With this, 2 bits ($\log_2 N_t$) can be transmitted during a symbol duration, same as the conventional SSK. In conventional SSK however, $\tau_i, i = 1, 2, \dots, N_t$ is kept the same for all possible symbols. It is worthy of note that the variable width can be employed to convey additional bits (further increase the data rate) in an SM fashion. But here it is used to provide resilience to channel correlation. By using the variable pulse width to provide an additional dimension for discerning the symbols, the error performance is thus improved while the data rate remains unchanged. Thus the duty cycle parameter τ_i becomes a design parameter that is assigned during the initial set-up stage, prior to the payload transmission. In some sense, this becomes a hybrid of SSK with pulse width modulation. In the event of clearly dissimilar channel gains, τ_i is chosen as the same for all N_t . Otherwise, each transmitter has a different pulse duty cycle and the system resembles a pulse width modulated system. This offers an additional design flexibility but at the cost of bandwidth expansion particularly for very small values of τ_i .

For an N_t -transmitter and N_r -receiver OWC configuration, the received signal can be expressed as:

$$\mathbf{r}(t) = R\mathbf{H}(t) \otimes \mathbf{x}(t) + \mathbf{n}(t) \quad (1)$$

where \otimes denotes convolution operation and $\mathbf{n}(t)$ is the N_r -dimensional noise vector. The noise is the sum of the receiver thermal noise and ambient light; it is modelled as independent and identically distributed additive white Gaussian noise (AWGN) while $\mathbf{x}(t)$ is the N_t -dimensional data signal. The

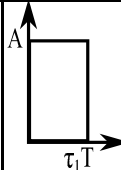
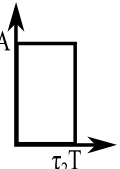
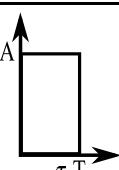
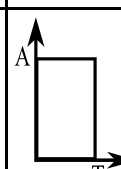
		Symbol (Bits)			
		0 (00)	1 (01)	2 (10)	3 (11)
L E D 1	LED 1		OFF	OFF	OFF
	LED 2	OFF		OFF	OFF
	LED 3	OFF	OFF		OFF
	LED 4	OFF	OFF	OFF	

Fig. 1. The electrical pulse pattern for the enhanced SSK using variable pulse width.

responsivity of the photodetector (PD) is given as R and the channel gain $\mathbf{H}(t)$ is:

$$\mathbf{H}(t) = \begin{bmatrix} h_{11}(t) & h_{12}(t) & \cdots & h_{1N_r}(t) \\ h_{21}(t) & h_{22}(t) & \cdots & h_{2N_r}(t) \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_t1}(t) & h_{N_t2}(t) & \cdots & h_{N_tN_r}(t) \end{bmatrix}^T \quad (2)$$

where $h_{ij}(t)$ is the channel gain between the i -th transmitter and the j -th receiver and T represents the transpose operation.

For illustration purposes, if we consider a 4-LED system with $N_r = 1$, then the received signal $r(t)$ is:

$$r(t) = s_m(t) + n(t) \quad (3)$$

where

$$s_m(t) = \begin{cases} h_{11}P_tR; & \text{for } m = 0, 0 \leq t \leq \tau_1T \\ h_{21}P_tR; & \text{for } m = 1, 0 \leq t \leq \tau_2T \\ h_{31}P_tR; & \text{for } m = 2, 0 \leq t \leq \tau_3T \\ h_{41}P_tR; & \text{for } m = 3, 0 \leq t \leq \tau_4T \end{cases} \quad (4)$$

In (4), P_t represents the transmitted optical power from a source driven by an electrical signal of amplitude A volts. By considering a correlator receiver architecture with a basis function $f(t) = \frac{1}{\sqrt{T}}$, thus the correlator output \mathbf{r}_b becomes:

$$\mathbf{r}_{bk} = \begin{cases} h_{11}RP_t\sqrt{T}\tau_1 + n_{b1}; & \text{for } m = 0 \\ h_{21}RP_t\sqrt{T}\tau_2 + n_{b2}; & \text{for } m = 1 \\ h_{31}RP_t\sqrt{T}\tau_3 + n_{b3}; & \text{for } m = 2 \\ h_{41}RP_t\sqrt{T}\tau_4 + n_{b4}; & \text{for } m = 3 \end{cases} \quad (5)$$

where $n_{bi}, i = 1, 2, \dots, N_t$ is the Gaussian noise at the output of the correlator with variance σ^2 . Using the maximum likelihood criterion, the estimated symbol \hat{d} is obtained as:

$$\begin{aligned} \hat{d} &= \arg \max_m p(\mathbf{r}_b | \mathbf{s}_m) \\ &= \arg \min_m D(\mathbf{r}_b, \mathbf{s}_m) \end{aligned} \quad (6)$$

where the joint probability density function of \mathbf{r}_b conditioned on \mathbf{s}_m being transmitted is given by:

$$p(\mathbf{r}_b | \mathbf{s}_m) = \frac{1}{(2\pi\sigma^2)^{N_r/2}} \exp \left[-\sum_{k=1}^{N_r} \frac{(r_{bk} - s_{mk})^2}{2\sigma^2} \right] \quad (7)$$

The Euclidean distance metric $D(\mathbf{r}_b, \mathbf{s}_m)$ is computed as follows:

$$D(\mathbf{r}_b, \mathbf{s}_m) = \sum_{k=1}^{N_r} (r_{bk} - s_{mk})^2 \quad (8)$$

where $s_{mk} = \int_0^\infty s_m(t)f(t) dt$, for $k = 1, 2, \dots, N_r$. The SER of the eSSKv can be derived by combining the pair-wise-error probability (PEP) with the union bound approach [13], [14] as follows:

Let $PEP_{j \rightarrow i}$ be the probability of deciding in favour of symbol i when symbol j was transmitted, then:

$$\begin{aligned} PEP_{j \rightarrow i} &= p(D(\mathbf{r}_b, \mathbf{s}_j) > D(\mathbf{r}_b, \mathbf{s}_i)) \\ &= p \left(2 \sum_{k=1}^{N_r} n_k (s_{ik} - s_{jk}) > \sum_{k=1}^{N_r} (s_{ik} - s_{jk})^2 \right) \\ &= Q \left(\frac{RP_t\sqrt{T}}{2\sigma} \sqrt{\sum_{k=1}^{N_r} (\tau_i h_{ik} - \tau_j h_{jk})^2} \right) \end{aligned} \quad (9)$$

Hence the symbol error performance union bound becomes:

$$P_{e,\text{sym}}^{\text{eSSKv}} \leq \frac{2}{N_t} \sum_{j=1}^{N_t-1} \sum_{i=j+1}^{N_t} Q \left(\sqrt{\frac{(RP_t)^2 2T}{4\sigma^2} \|\tau_i h_{ik} - \tau_j h_{jk}\|_F^2} \right) \quad (10)$$

where $\|\cdot\|_F$ is the Frobenius norm. In selecting the appropriate value of τ at the set-up stage, the objective is to maximise the value of $\|\tau_i h_{ik} - \tau_j h_{jk}\|_F^2$. For the eSSKv, the average electrical signal-to-noise ratio (SNR) per symbol γ_{eSSKv} is defined as:

$$\gamma_{\text{eSSKv}} = \frac{(RP_t)^2 \sum_{i=1}^{N_t} \tau_i}{N_t \sigma^2} \quad (11)$$

The average SNR for the SSK can be obtained from (11) by setting $\tau_i = 1$ for all i .

B. Optical SSK with Pulse Inversion (eSSKi)

Although with an appropriate choice of τ_i it is possible to improve the error performance of SSK with the eSSKv, there exists the possibility of reduced spectral efficiency particularly when τ_i is small. To avoid this, the eSSKi can be used. It offers the same spectral efficiency as the SSK but with much improved error performance. This is achieved by increasing the effective distance between the constellation points. In effect, the eSSKi trades overall power efficiency for spectral efficiency. As shown in Fig. 2 for the case of $N_t = 4$ transmitters, eSSKi uses non-return-to-zero signalling just like the conventional SSK. But the even-indexed transmitters are driven with electrical pulses of amplitude $-A$ volts while the odd indexed ones have electrical pulses with amplitude A volts. The essence of this is to increase the distance between adjacent constellation points.

		Symbol (Bits)			
		0 (00)	1 (01)	2 (10)	3 (11)
L E D 1	A		OFF	OFF	OFF
	T	OFF		OFF	OFF
	A	OFF	OFF		OFF
	T	OFF	OFF	OFF	
L E D 2	A	OFF		OFF	OFF
	T	OFF	OFF		OFF
	A	OFF	OFF		OFF
	T	OFF	OFF	OFF	
L E D 3	A	OFF	OFF		OFF
	T	OFF	OFF	OFF	
	A	OFF	OFF		OFF
	T	OFF	OFF	OFF	
L E D 4	A	OFF	OFF	OFF	
	T	OFF	OFF	OFF	
	A	OFF	OFF	OFF	
	T	OFF	OFF	OFF	

Fig. 2. The electrical pulse pattern for the enhanced SSK using pulse inversion.

Being a bipolar signalling technique, the eSSKi does require a DC bias. This requirement leads to a reduction in its overall power efficiency in comparison to the SSK. For VLC applications however, this is unlikely to be a disadvantage as the LEDs will have to be biased anyway to provide illumination.

By following the same approach as in the previous section, the SER of the eSSKi is derived as:

$$P_{e,\text{sym}}^{\text{eSSKi}} \leq \frac{2}{N_t} \sum_{j=1}^{N_t-1} \sum_{i=j+1}^{N_t} Q \left(\sqrt{\frac{(RP_t)^2 T}{4\sigma^2}} \|a_i h_{ik} - a_j h_{jk}\|_{\text{F}}^2 \right) \quad (12)$$

where $a_l = +1$ for $l = \text{odd}$, otherwise $a_l = -1$. For the eSSKv, the average SNR per symbol γ_{eSSKi} is defined as:

$$\gamma_{\text{eSSKi}} = \frac{(RP_t)^2}{\sigma^2} \quad (13)$$

The two enhancement techniques of eSSKi and eSSKv make the conventional SSK adaptive. That is, the transmitter can choose the appropriate pulse feature based on the channel condition and the system constraints of power and spectral efficiency requirements.

IV. RESULTS AND DISCUSSIONS

To evaluate the link performance, we will first be considering the benchmark conventional SSK. The results presented here will be based on an $N_t = 4$ and $N_r = 1$ optical wireless communication configuration. All the analytical results presented are also validated with Monte Carlo simulations. To demonstrate the link performance under identical channel gains, $\{h_{i1}\}_{i=1}^4 = [1, 0.99, 0.9, 0.89]$ will be used while $\{h_{i1}\}_{i=1}^4 = [1, 0.8, 0.6, 0.4]$ will be used for the case of uncorrelated channel.

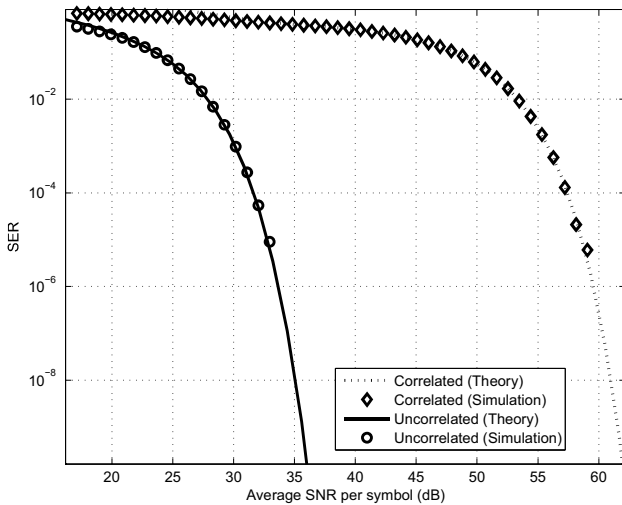


Fig. 3. The average SNR per symbol against the SER for conventional SSK with and without correlated channel gains.

From Fig. 3 where we show the SER of the conventional SSK at different SNR values, it can be observed that under the given parameters, the SER deteriorates with correlated channel gains. When the channel gains are correlated and very close, it becomes difficult to discern the transmitting LED at the receiver. For example at an SER of 10^{-6} and the specified channel gains, about 25 dB of extra SNR is required

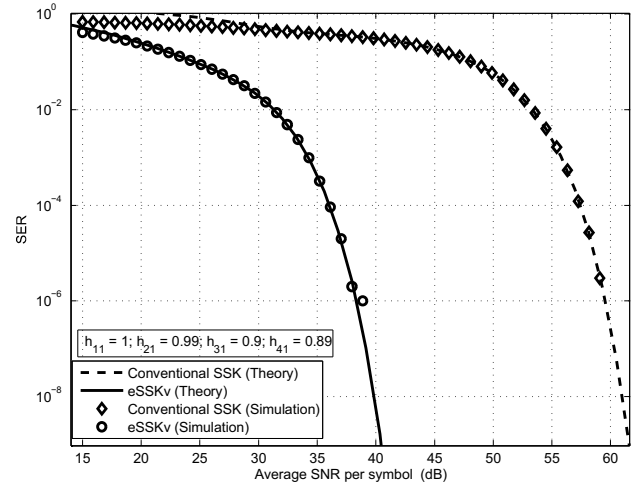


Fig. 4. The average SNR per symbol against the SER for four sources and one receiver: the enhanced SSK with variable pulse width with $\{\tau_i\}_{i=1}^4 = [1, 0.8, 0.6, 0.5]$ and conventional SSK for $\{h_{i,1}\}_{i=1}^4 = [1, 0.99, 0.9, 0.89]$.

under correlated channel conditions to achieve the same error performance as when the channel gains are clearly distinctive.

To reduce this power penalty, we will now consider the enhancements of section III. For the variable pulse width enhancement, for any given set of h_{ij} , the best of choice of τ_i is that which maximises $\|\tau_i h_{ik} - \tau_j h_{jk}\|_{\text{F}}^2$. Based on this condition, we will be considering $\{\tau_i\}_{i=1}^4 = [1, 0.8, 0.6, 0.5]$ for the identical channel gains case. With these pulse width values, it is possible to reduce the SER required by SSK in correlated channel conditions by about 20 dB at an SER of 10^{-6} as Fig. 4 illustrates. This is brought about by the additional differentiation the variable pulse width introduces to the signals from the different LEDs. Under this channel correlation condition, the ultimate gain in terms of average SNR from the eSSKv enhancement depends strongly on the choice of τ_i .

For the second enhancement technique, we show in Fig. 5 the error performance under the same closely-related channel gains. Here, considering the same SER of 10^{-6} , a reduction in average SNR per symbol of about 18 dB could be achieved over the SSK. This is achieved by inverting the electrical pulse that feeds the even indexed transmit LEDs. It should be highlighted that this type of enhancement requires an additional DC bias to make the inverted pulse positive. This inverted pulse technique can indeed be applied even when the channel gains are not so close as shown in Fig. 6. For the given channel gains in this figure, a gain of 7 dB in electrical SNR over the regular SSK can still be achieved at the benchmark SER of 10^{-6} .

V. CONCLUSION

In this paper, an adaptive SSK modulation has been introduced to provide improved error over the conventional SSK in

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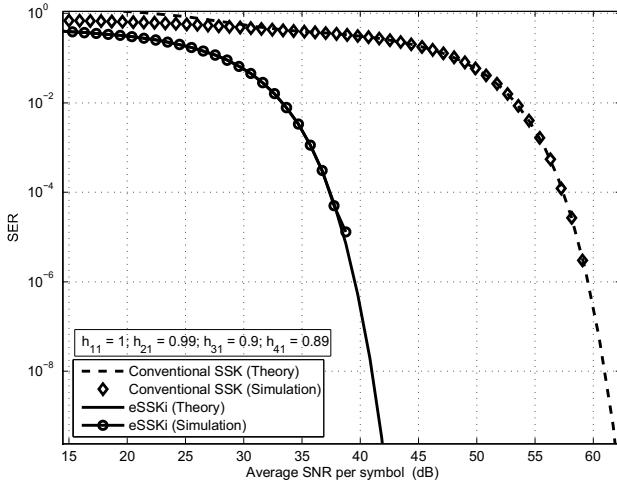


Fig. 5. The average SNR per symbol against the SER for four sources and one receiver: the enhanced SSK with pulse inversion and conventional SSK for $\{h_{i,1}\}_{i=1}^4 = [1, 0.99, 0.9, 0.89]$.

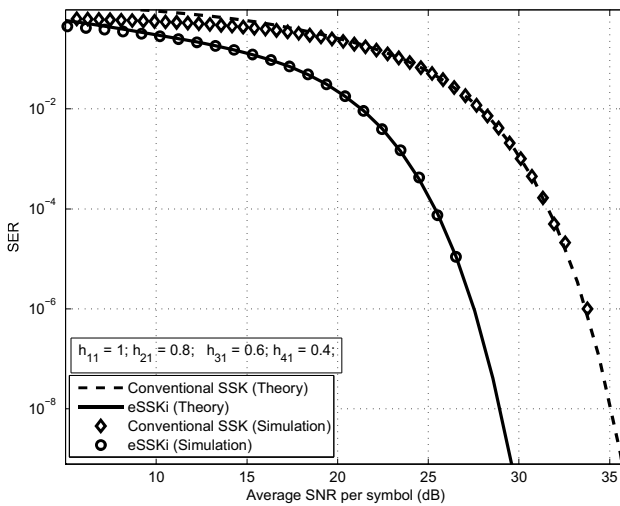


Fig. 6. The average SNR per symbol against the SER for four sources and one receiver: the enhanced SSK with pulse inversion and conventional SSK for $\{h_{i,1}\}_{i=1}^4 = [1, 0.8, 0.6, 0.4]$.

the event of correlated channel gains. In one variant, different LEDs use different pulse widths (eSSKv) while the other approach uses pulse inversion (eSSKi) to offer resilience to channel correlation. Closed form expressions have also been given for the techniques and these have been verified with computer based simulations.

In a four-LED, one-receiver configuration with correlated channel gains $\{h_{i,1}\}_{i=1}^4 = [1, 0.99, 0.9, 0.89]$, the enhancement techniques can produce a reduction of up to 20 dB in electrical SNR at and SER of 10^{-6} when compared with the conventional SSK.